APPENDIX II

CONSTRAINED-ENVELOPE DIGITAL-COMMUNICATIONS TRANSMISSION SYSTEM AND METHOD THEREFOR

TECHNICAL FIELD OF THE INVENTION

The present invention relates generally to the field of digital communications. More specifically, the present invention relates to the field of constrained-envelope digital transmitter circuits.

BACKGROUND OF THE INVENTION

A wireless digital communications system should ideally refrain from using any portion of the frequency spectrum beyond that actually required for communications. Such a maximally efficient use of the frequency spectrum would allow the greatest number of communications channels per given spectrum. In the real-world, however, some spectral regrowth (i.e., increase in spectral bandwidth) is inevitable due to imperfect signal amplification.

In wireless communication systems various methodologies have been used to minimize spectral regrowth. Some conventional methodologies utilize complex digital signal processing algorithms to alter a digitally modulated transmission signal in some manner conducive to minimal spectral regrowth. Such complex algorithmic methodologies are well suited to low-throughput applications, i.e., those less than 0.5 Mbps (megabits per second), such as transmission of vocoder or other audio data. This is because the low throughput rate allows sufficient time between symbols for the processor to perform extensive and often repetitive calculations to effect the required signal modification. Unfortunately, high-throughput applications, i.e., those greater than 0.5 Mbps, such as the transmission of high-speed video data, cannot use complex processing algorithms because the processing power required to process the higher data rate is impractical.

A digital signal processing methodology may be used with the transmission of burst signals. With burst transmissions, the interstitial time between bursts may be used to perform the necessary complex computations based upon an entire burst. This methodology is not practical when continuous (as opposed to burst) transmission is used.

A conventional form of post-modulation pulse shaping to minimize spectral bandwidth utilizes some form of Nyquist-type filtration, such as Nyquist, root-Nyquist, raised cosine-rolloff etc. Nyquist-type filters are desirable as they provide a nearly ideal spectrally constrained waveform and negligible inter-symbol interference. This is achieved by spreading the datum for a single constellation phase point over many unit baud intervals in such a manner that the energy from any given phase-point datum does not interfere with the energy from preceding and following phase-point data at the appropriate baud-interval sampling instants.

The use of Nyquist-type filtration in a transmission circuit produces a filtered signal stream containing a pulse waveform with a spectrally constrained waveform. The degree to which a Nyquist-type pulse waveform is constrained in bandwidth is a function of the excess bandwidth factor, α. The smaller the value of α, the more the pulse waveform is constrained in spectral regrowth. It is therefore desirable to have the value of α as small as possible. However, as the value of α is decreased, the ratio of the spectrally constrained waveform magnitude to the spectrally unconstrained waveform magnitude is increased. The spectrally unconstrained waveform is the waveform that would result if no action were taken to reduce spectral regrowth. Typical designs use α values of 0.15 to 0.5. For an exemplary α value of 0.2, the magnitude of the spectrally constrained waveform is approximately 1.8 times that of the unconstrained waveform. This means that, for a normalized spectrally unconstrained waveform magnitude power of 1.0, the transmitter output amplifier must actually be able to provide an output power of 3.24 (1.8^2) to faithfully transmit the spectrally constrained waveform. This poses several problems.

When the transmitter output amplifier is biased so that the maximum spectrally unconstrained waveform (1.0 normalized) is at or near the top of the amplifier's linear region, all "overpower" will be clipped as the amplifier saturates. Such clipping causes a marked increase in spectral regrowth, obviating the use of Nyquist-type filtration.

When the transmitter output amplifier is biased so that the maximum spectrally constrained waveform (1.8 normalized) is at or near the top of the amplifier's linear region, the spectrally unconstrained waveform is at only 56 percent (i.e., $1/1.8$) of the amplifiers peak linear power. This results in an inefficient use of the output amplifier.

Also, the biasing of the transmitter output amplifier so that the spectrally constrained waveform is at or near the top of the amplifier's linear region requires that the output amplifier be of significantly higher power than that required for the transmission of a spectrally unconstrained waveform. Such a higher-power amplifier is inherently more costly than its lower-power counterparts.

SUMMARY OF THE INVENTION

It is an advantage of the present invention that a circuitry and a methodology are provided that allow a transmitter output amplifier to be biased so that the spectrally unconstrained waveform is at or near the top of the amplifier's linear region without incurring clipping of a spectrally constrained waveform.

It is another advantage of the present invention that a circuitry and methodology are provided that allow a spectrally constrained waveform to have approximately the same magnitude as the spectrally unconstrained waveform without effecting a significant increase in spectral regrowth.

It is another advantage of the present invention that a circuitry and methodology are provided which allow a spectrally constrained waveform to be utilized with a continuous transmission scheme.

It is another advantage of the present invention that a circuitry and methodology are provided which allow efficient use of a transmitter output amplifier, thus allowing higher power output for a given output amplifier and a given bandwidth constraint than was previously feasible.

It is another advantage of the present invention that a circuitry and methodology are provided which allow efficient use of a transmitter output amplifier, which allows allowing a lower-power amplifier to be used for achieving given bandwidth constraints than was previously feasible, thus effecting a significant saving in the cost thereof.

These and other advantages are realized in one form by a constrained-envelope digital communications transmitter circuit. The transmitter circuit has a pulse-spreading filter configured to receive a quadrature phase-point signal stream of digitized quadrature phase points and produce a filtered signal stream, which filtered signal stream exhibits energy corresponding to each phase point spread throughout a plurality of baud intervals. The transmitter circuit also has a constrained-envelope generator coupled to the pulse-spreading filter and configured to produce a constrained-methodology of the present invention may be applied to all forms of constellations. The present invention is especially beneficial when used with constellations having rings of different magnitudes, i.e., amplitude and phase-shift keying (APSK) constellations. This is true because APSK constellations, requiring amplitude modulation of the signal, desirably use linear amplifiers to reproduce that amplitude modulation.

Each phase point **54** in constellation **46** represents a plurality, in this example four, of symbols. The values of the symbols in a given phase point **54** determine the location of that phase point **54** within constellation **46** in a manner well known to those skilled in the art.

Each quadrature phase point **54** may be thought of as having a vector value expressed as I,Q in the Cartesian coordinate system, where I is the in-phase (abscissa) value and Q is the quadrature (ordinate) value of the vector, or expressed as M,ϕ in the polar coordinate system, where M is the magnitude and ϕ is the phase angle of the vector. In this discussion, the M,ϕ designation will be used throughout, as the vector magnitude is the most discussed vector component.

In the exemplary 16-P-APSK constellation **46** of FIG. **3**, each phase point **54** resides upon an outer ring **56** or an inner ring **58**. Phase-points **54** residing upon outer ring **56** are outer-ring or maximum-magnitude phase points **60**. That is, outer-ring phase points **60** have a maximum magnitude (maximum value of M) as represented by the radius of outer ring **56**. For purposes of discussion, the magnitudes of outer-ring phase points **60** are normalized to 1.00.

Inner-ring phase points **62**, i.e., those phase points **54** residing upon inner ring **58**, have a lesser magnitude as represented by the radius of inner ring **58**. For the exemplary 16-P-APSK constellation **46** depicted in FIG. **3**, the magnitudes of inner-ring phase points **62** may desirably be approximately 0.63 when outer-ring phase point **60** magnitudes are normalized to 1.00.

FIG. **4** depicts a plurality of signal streams, in accordance with a preferred embodiment of the present invention. The following discussion refers to FIGS. **2** through **4**.

The output of phase mapper **44** is phase-point signal stream **50**. Phase mapper **44** processes one phase point **54** per unit baud interval **64**. That is, phase-point signal stream **50** consists of a series of consecutive phase-point pulses **66**, each of which represents one phase point **54**, whose leading edges are one unit baud interval **64** apart. Those skilled in the art will appreciate that other embodiments of phase-point signal stream **50** are equally valid, that the embodiment utilized is dependent upon the circuitry producing and processing phase-point signal stream **50**, and that the use of other embodiments of this or any other signal stream does not depart from the spirit of the present invent nor the scope of the appended claims.

FIGS. **3** and **4** illustrate a series of twelve exemplary sequential phase points **52**, representative of a random data stream processed by transmitter circuit **22** (FIG.**2**). These twelve exemplary phase points **52** reside at temporally consecutive locations labeled t_0, t_1, t_2, t_3, t_4, t_5, t_6, t_7, t_8, t_9, t_{10}, and t_{11}. These labels represent sequential integral times at unit baud intervals **64**, i.e., integral-baud times, and indicate the leading-edge times of phase-point pulses **66**. For purposes of simplification within this discussion, any occurrence at time t_N shall be referred to as "occurrence t_N". For example, an exemplary phase point **52** occurring at time t_2 shall be referred to as phase point t_2, and the associated phase-point pulse **66** whose leading edge occurs at time t_2 shall be referred to as phase-point-signal pulse t_2. In other words, at time t_2, phase point t_2 is clocked and phase-point-signal pulse t_2 begins. One unit baud interval **64** later, at time t_3, phase point t_3 is clocked and phase-point pulse t_3 begins. This process continues indefinitely, with twelve exemplary phase points t_0 through t_{11} depicted in FIG. **3** and twelve corresponding phase-point-signal pulses t_0 through t_{11} depicted in phase-point signal stream **50** of FIG. **4**.

Table 1 below illustrates the magnitudes for phase-point-signal pulses to through t_{11}.

TABLE 1

Phase-Point Pulse Magnitudes

Phase-Point-Signal Pulse	Magnitude
t_0	Outer-Ring 68
t_1	Inner-Ring 70
t_2	Outer-Ring 68
t_3	Outer-Ring 68
t_4	Inner-Ring 70
t_5	Outer-Ring 68
t_6	Outer-Ring 68
t_7	Outer-Ring 68
t_8	Outer-Ring 68
t_9	Inner-Ring 70
t_{10}	Outer-Ring 68
t_{11}	Inner-Ring 70

Phase point t_0 is an outer-ring phase point **60**. Phase-point-signal pulse to therefore has an outer-ring magnitude **68**. In like manner, phase point t_1 is an inner-ring phase point **62** and phase-point-signal pulse t_1 has an inner-ring magnitude **70**.

Phase-point signal stream **50** effects locus **48** through constellation **46**. Locus **48** coincides with the location of each exemplary phase point t_0 through t_{11} in turn at unit baud intervals **64**. In FIG. **3**, locus **48** is depicted as effecting a minimum distance (straight line) path between adjacent exemplary phase points **52**. Those skilled in the art will appreciate that locus **48** is so depicted solely for the sake of simplicity, and that in actual practice, locus **48** instantly jumps or snaps between exemplary phase points **52** in a discontinuous manner.

FIG. **5** depicts an expanded phase-point constellation **46'** illustrating a locus **72** of a filtered signal stream **74** (FIG. **2**) over twelve exemplary sequential phase points **52** in accordance with a preferred embodiment of the present invention. The following discussion refers to FIGS. **2** through **5**.

In the preferred embodiment, phase-point signal stream **50** passes to the input of a pulse-spreading filter **76**, preferably realized as a Nyquist-type filter, such as a Nyquist, root-Nyquist, raised cosine-rolloff, etc., filter. Pulse-spreading filter **76** filters phase-point signal stream **50** into filtered signal stream **74**, depicted in FIG. **5**. In orthogonal frequency division multiplex (OFDM) systems, also known as multitone modulation (MTM) systems, pulse-spreading filter **76** may be implemented using a transmultiplexer or equivalent circuitry.

In accordance with Shannon's theory, well known to those skilled in the art, pulse-spreading filter **76** produces at least two (only two in the preferred embodiment) output filtered-signal pulses **78**, i.e., complex samples of filtered signal stream **74**, for each input phase-point pulse **66** received. This is demonstrated in FIG. **4** where filtered signal stream **74** possesses two filtered-signal pulses **78** per unit baud interval **64**. In the preferred embodiment, filtered-signal pulses **78** consist of alternating on-time pulses **80**, i.e., samples of filtered signal stream at integral unit baud intervals **64**, and off-time pulses **82**, i.e., samples of filtered signal stream **74** between integral unit baud intervals. In effect, filtered signal stream **74** is made up of two interleaved data streams, an on-time signal stream **84** and an off-time signal stream **86**.

On-time signal stream **84** is substantially a version of phase-point signal stream **50**, wherein each phase-point pulse **66** has been reduced in duration from one unit baud interval **64** to a half-unit baud interval **88** to become on-time pulse **80** while maintaining substantially the same relative leading-edge time. That is, filtered-signal pulse to has substantially the same magnitude and substantially the same leading edge time as phase-point pulse to with approximately one-half the duration. Of course, those skilled in the art will appreciate that signal streams **74** and **84** may be delayed from signal stream **50** by a delay imposed by filter **76**.

The generation of both on-time pulses **80** and off-time pulses **82** by pulse-spreading filter **76** effectively populates expanded constellation **46'** (FIG. **5**) with on-time phase-points **90** (circles) and off-time phase points **92** (squares). The original phase points **54** of constellation **46** (FIG. **3**), i.e., the phase points carrying the intelligence to be communicated by transmitter circuit **22**, are on-time phase points **90** of expanded constellation **46'**.

Added to expanded constellation **46'** are off-time phase points **92**, with each off-time phase-point **92** occurring approximately midway in time between consecutive on-time phase points **90**. Therefore, exemplary sequential phase points **52** become exemplary filtered phase points **94**. Exemplary filtered phase points **94** are made up of alternating exemplary on-time filtered phase points **96** and exemplary off-time filtered phase points **98**, and reside at temporally consecutive locations labeled t_0, $t_{0.5}$, t_1, $t_{1.5}$, t_2, $t_{2.5}$, t3, $t_{3.5}$, t_4, $t_{4.5}$, t_5, $t_{5.5}$, t_6, $t_{6.5}$, t_7, $t_{7.5}$, t_8, $t_{8.5}$, t_9, $t_{9.5}$, t_{10}, $t_{10.5}$, and t_{11}, In FIG. **5**, exemplary on-time filtered phase points **96** are located at integral-baud times (t_0, t_1, t_2, etc.), whereas exemplary off-time filtered phase points **98** are located at fractional-baud (non-integral-baud) times ($t_{0.5}$,$t_{1.5}$, $t_{2.5}$, etc.).

The generation of off-time phase points **92** approximately midway in time between consecutive on-time phase points **90** causes filtered signal locus **72** to effect excursions having local peak magnitudes **99** greater than outer-ring magnitude **68**. Such excursions occur because the immediate position of locus **72** at any given instant in time is not only a result of those phase points **54** proximate that position, but of a plurality of phase points **54** both preceding and following that instant in time. That is, in the preferred embodiment, the determination of the position of locus **72** at time $t_{2.5}$ (i.e., coincident with off-time phase point $t_{2.5}$) is determined not only by the positions of phase points t_2 and t_3, but by the positions of numerous phase points **54** preceding phase point $t_{2.5}$ (i.e., phase points t_2, $t_{1.5}$, t_1, $t_{0.5}$, etc.) and the positions of numerous phase points **54** following phase point $t_{2.5}$ (i.e., phase points t_3, $t_{3.5}$, t_4, $t_{4.5}$, etc.)

This phenomenon is illustrated in FIG. **6**, which depicts a pair of Nyquist-type datum bursts **100** in accordance with a preferred embodiment of the present invention. The following discussion refers to FIGS. **2**, **4**, **5**, and **6**.

In the preferred embodiment, pulse-spreading filter **76** is realized as a Nyquist-type filter. Therefore, when a single phase-point pulse **66** is filtered by pulse-spreading filter **76**, that single pulse **66** is transformed into a Nyquist-type datum burst **100** extending over a plurality of unit baud intervals **64**. It is a property of Nyquist-type filters that datum burst **100** attains a datum-burst peak value **102** (i.e., a local peak magnitude) at the primary sampling time of the specific phase-point pulse **66** (i.e., at time t_2 for phase-point pulse t_2), and attains a zero datum-burst value **104** (i.e., is equal to zero) at integral unit baud intervals **64** preceding and following peak datum-burst value **102** (i.e., at times . . . , t_{-1}, t_0, t_1, and t_3, t_4, t_5, . . . , for phase point pulse t_2). In this manner, the energy of each pulse **78** is spread over a plurality of baud intervals **64** preceding and following the clocking instant (time t_2).

FIG. **6** illustrates Nyquist-type datum bursts **100** for phase-point pulses t_2 and t_3, with datum burst t_2 depicted as a solid line and datum burst t_3 depicted as a dashed line. As an example, it may be seen from FIG. **6** that at time t_2 the value of datum burst t_2 is peak datum-burst value **102**. At every other time separated from time t_2 by an integral number of unit baud intervals **64**, the value of datum burst t_2 is zero. An analogous condition occurs for datum burst t_3.

The value of locus **72** is, at each moment in time, the sum of all datum bursts **100** at that moment. In the simplified two-datum-burst example of FIG. **6**, locus **72**, depicted by a dotted line, is the sum of datum burst t_2 and datum burst t_3. Since datum bursts t_2 and t_3 are zero at each integral time t_N except times t_2 and t_3, the value of locus **72** is also zero except at times t_2 and t_3, where it assumes the peak values of datum bursts t_2 and t_3, respectively.

The value of locus **72** at any instant in time between integral-baud times is the sum of the values of all datum bursts **100** at that instant. For example, in FIG. **6** where only two datum bursts **100** are considered, locus **72** has a value at time $t_{2.5}$ that is the sum of the values of datum bursts t_2 and t_3 at time $t_{2.5}$. Since datum bursts t_2 and t_3 both have significant positive values at time $t_{2.5}$, locus **72** has a value significantly greater than the maximum values of either datum burst t_2 or datum burst t_3.

Since locus **72** describes the sum of all datum bursts **100**, locus **72** is a function of the shape of the curves (FIG.**6**) describing those datum bursts **100**. That is, locus **72** is a function of a filtered-signal peak magnitude component of a filtered-signal complex digital value at any given point. The shape of the datum-burst curve is a function of the excess bandwidth factor, α, a design property of pulse-spreading filter **76**. The smaller the value of α, the more locus **72** may rise above the peak datum burst values **102** of adjacent datum bursts **100**. Typical designs of pulse-spreading filters **76** use α values of 0.15 to 0.5. For like-valued adjacent phase points **54** and an α value of 0.2, a maximum excursion magnitude **105** (i.e., the potential local peak magnitude **99** of locus **72**) is approximately 1.8 times the value of the maximum phase-point magnitude. That is, the magnitude of the constrained envelope is approximately 1.8 times that of the unconstrained envelope. In the preferred embodiment depicted in FIGS. **3**, **4**, and **6**, on-time phase points t_2 and t_3 are both outer-ring phase points **60** having a normalized outer-ring magnitude **68** of 1.00. Therefore, off-time phase point $t_{2.5}$ may have a normalized maximum excursion magnitude **105** of 1.8. This implies that transmitter circuit **22**, to faithfully transmit phase point $t_{2.5}$ without excessive distortion, and without the benefit of the present invention, would require an output power of 3.24 (1.8^2) times the power required to transmit phase point t_2 or t_3, which are representative of the highest magnitude intelligence-carrying phase points **54**. This represents an inefficient use of available power.

The following discussion refers to FIGS. **2**, **4**, and **5**.

Off-time signal stream **86**, a portion of filtered signal stream **74**, passes from an output of pulse-spreading filter **76** dent with said difference pulses of said difference signal stream, and wherein, when ones of said difference pulses have said first-polarity difference-pulse values, said coincident error pulses have error-pulse values substantially equal to said first-polarity difference-pulse values, and when ones of said difference pulses have said second-polarity difference-pulse values, said coincident error pulses have error-pulse values substantially equal to zero; and

a second Nyquist-type filter coupled to said discriminator and configured to produce said constrained-bandwidth error signal stream.

25. A digital-communications transmitter circuit as claimed in claim **24** wherein said transmitter circuit additionally comprises:

a convolutional encoder coupled to said binary data source and configured to produce an encoded signal stream; and

an interleaver coupled to said convolutional encoder and configured to produce an interleaved signal stream by temporally decorrelating said encoded signal stream.

26. A digital-communications transmitter circuit as claimed in claim **24** wherein:

said filtered signal stream is a quadrature signal stream having a locus that passes proximate one of said phase points of said phase-point constellation at integral unit baud intervals;

said first filtered-signal data stream comprises on-time samples of said filtered signal stream, each of said on-time samples occurring substantially coincidentally with said passage of said filtered signal locus proximate one of said phase points of said phase-point constellation; and

said second filtered-signal data stream comprises off-time samples of said filtered signal stream wherein each of said off-time samples occurs between adjacent ones of said on-time samples.

27. A digital-communications transmitter circuit as claimed in claim **26** wherein each of said off-time samples occurs substantially midway between adjacent ones of said on-time samples.

28. A digital-communications transmitter circuit as claimed in claim **23** additionally comprising an interleaver coupled to said binary data source and configured to provide an interleaved signal stream.

29. A digital-communications transmitter circuit as claimed in claim **23** wherein said constellation is an amplitude and phase shift keying constellation.

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